Interplanetary causes of very intense magnetic storms

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Abstract. Possible interplanetary mechanisms for the creation of very intense magnetic storms are discussed. We examine the effects of a combination of a long-duration southward sheath magnetic field, followed by a magnetic cloud B_s event. We also consider the effects of interplanetary shock events on the sheath plasma. Examination of profiles of very intense storms from 1957 to the present indicate that double, and sometimes triple, IMF B_s events are important causes of such events. We also discuss evidence that magnetic clouds with very intense core magnetic fields tend to have large velocities, thus implying large amplitude interplanetary electric fields that can drive very intense storms.

1. Introduction

In this paper we examine the causes of the largest magnetic storms at Earth (as measured by Dst). We know that the energy transfer mechanism from the solar wind to the magnetosphere for magnetic storms is magnetic reconnection between the interplanetary magnetic field and the Earth's field, where the interplanetary dawn-dusk electric field is given by $\mathbf{V_{sw}} \times \mathbf{Bs}$ [Dungey, 1961; Gonzalez et al., 1994]. In the above expression, V_{sw} is the solar wind velocity and B_s is the southward component of the interplanetary magnetic field (IMF). However, there has been little effort placed to date on understanding the detailed causes of very intense magnetic storms. Are the velocities unusually high? Are the magnetic fields unusually intense or do both the velocity and magnetic fields have to be large to create superintense storms? Do double (or triple) shock events create very high magnetic fields? Or are there other causes of these unusually intense storm events?

2. Fast ICME Magnetic Fields

It has been shown that a southward IMF < -10 nT (>5 mV/m) for $T > 3$ hours is typically needed for the creation of an intense ($Dst < -100$ nT) magnetic storm [Gonzalez and Tsurutani, 1987]. Although this empiri-

cal relationship was originally demonstrated for the solar maximum epoch, it has been shown to hold for solar minimum as well [Tsurutani et al., 1995]. The southward IMF events can be located either in the sheath fields ahead of fast interplanetary coronal mass ejections (ICMEs) or within the ICMEs themselves. The latter case, intense B_s, within an ICME, is usually in the form of a magnetic cloud [Burlaga et al., 1981]. A schematic of this overall geometry is given in Figure 1.
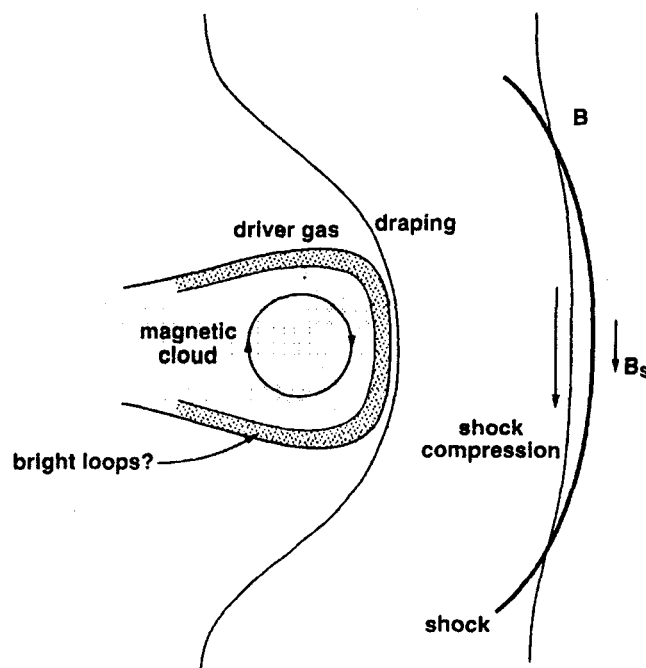

Figure 1. Schematic showing geometry of a magnetic cloud, sheath field, shock and upstream magnetic field.

There are reasons to expect stronger magnetic fields in both interplanetary regions for fast ICMEs. A fast driver gas will in general lead to stronger shock-

compressed magnetic fields (depending on the upstream flow conditions). The magnetic field compression across the shock can be up to a maximum of 4.0 [*Kennel et al.*, 1985]. If the upstream IMF has a southward orientation, the shock leads to intensification of this component.

Gonzalez et al., [1998] have found a general relationship between the speed of the ICME and the magnetic field intensity in the magnetic cloud. To examine this relationship quantitatively, *Gonzalez et al.* combined published examples of clouds with those observed by the ISEE-3 satellite in 1979 and identified following the criteria given by *Burlaga*, [1995]. Figure 2 displays the cloud field intensity versus the cloud velocity for all these events. This figure shows that there is a clear tendency for the cloud to have higher magnetic fields the faster it propagates relative to inertial space. At this time, the physical causes of the relationship between the cloud's $|B|$ and V_{sw} are uncertain. Compression of the cloud is certainly occurring, but it is uncertain whether all of the field increase can be accounted for by such an effect. Another possibility is that this relationship may be related to the CME release and acceleration mechanisms at the Sun. The $|B|$–V_{sw} relationship may give important clues as to these mechanisms.
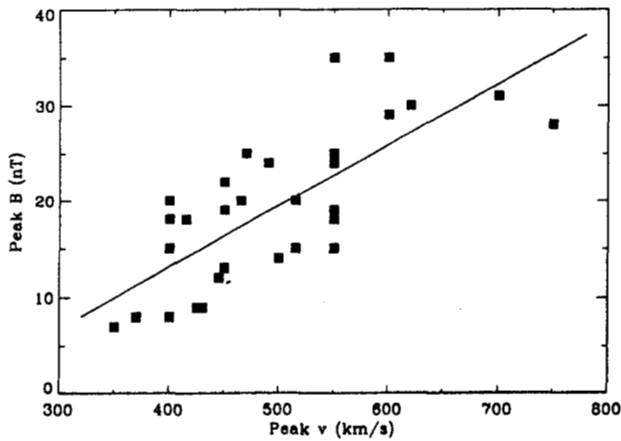
Figure 2. Peak values of the magnetic field and velocity for the cloud events studied by *Gonzalez et al.*, [1998]

Figure 3 displays the ISEE-3 subset of driver gas-non cloud events also studied by *Gonzalez et al.*, [1998]. One can see that this plot is largely scattered without any clear trend for a $|B| - V_{sw}$ relationship, as that shown in Figure 2 for the cloud events. An explanation for this different behavior is also presently unknown.
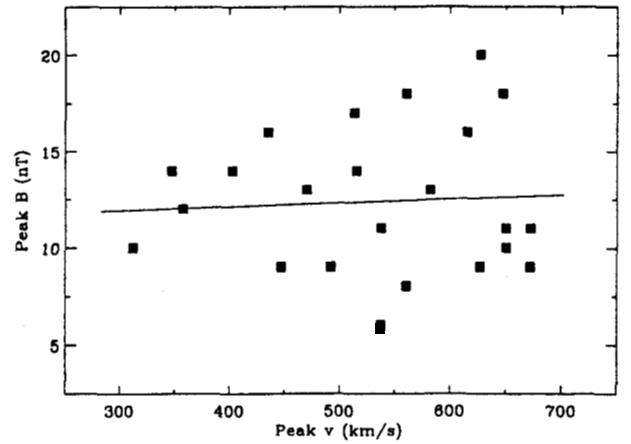
Figure 3. Peak values of the magnetic field and velocity for the driver gas-non cloud events of 1979, as measured by the ISEE-3 satellite, and reported by *Gonzalez et al.*, [1998].

3. Interplanetary Shock Effects

One mechanism to create even higher field strengths would be for a second interplanetary shock to (further) compress the high fields existing in the ICME/sheath regions (of Figure 1). An argument was presented in *Tsurutani and Gonzalez* [1997] that the presence of shocks/strong compressions may not be possible within magnetic clouds because of the low beta conditions present there. Typical beta values in clouds are 0.1 with consequential Alfvén/magnetosonic speeds of 300-700 Km/s . These high speeds would ordinarily preclude the formation of shocks within magnetic clouds.

Another mechanism to have shocks occurring within sheaths is to have the shocks propagate from the downstream magnetosheath up into the front side sheath regions. To determine what the possibility of each of these mechanisms might be, simulation efforts are recommended.

Shock compression of sheath fields has been previously observed. Figure 4 shows the magnetic field for the August 1972 event at Pioneer 10 (2.2 AU). At this distance, the highest field strengths (-18 nT) are associated with this process. The first shock compresses the ambient magnetic field by 4 times and the second shock by 2 times. Exactly how this second shock was present in the sheath is not known.

The August 1972 interplanetary event had a velocity greater than 1500 Km/s at 1 AU (the plasma instruments were saturated). The magnetic cloud field strength reached 16 nT at 2.2 AU, corresponding to 51 nT at 1 AU (assuming a $r^{-1.7}$ radial dependence). The field at 1 AU would be higher if a steeper dependence is assumed. Note that this $|B|$–V_{sw} relation is in general agreement with the trend of Figure 2. The magnetic

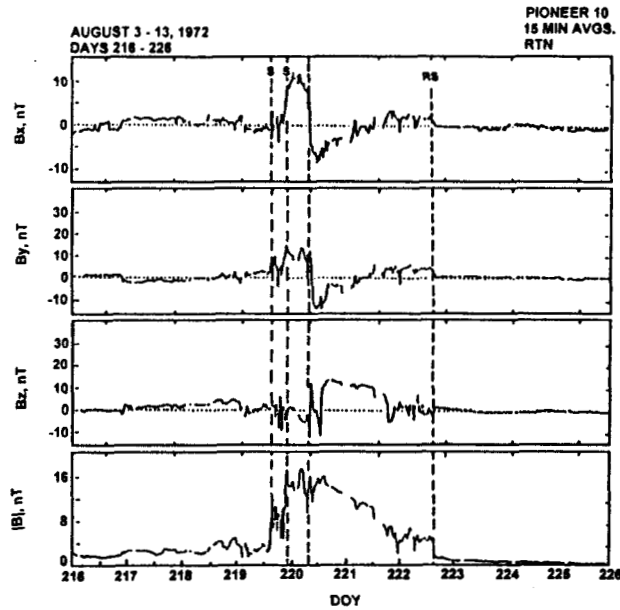field was plotted in solar heliospheric, or RTN, coordinates.

Figure 4. Pioneer 10 IMF data at 2.2 AU from the sun [from *Smith and Sonett*, 1976].

4. Double and Triple-Step Storms

Another way to get large *Dst* events is to have two storm main phases with the second closely following the first. *Kamide et al.* [1998] in an analysis of more than 1200 magnetic storms have shown that such events are quite common and are caused by two IMF southward field events of approximately equal strength. This is shown in Figure 5. The magnetic field is in GSM coordinates. *Kamide et al.* argue that this could also be viewed as two moderate magnetic storms with the *Dst* base of the second well below that of the first. *Grande et al.* [1996] and *Daglis* [1997] have studied the March 23, 1991 double magnetic storm using CRRES ion composition data. *Grande et al.* point out that the first event is dominated by Fe^{+9}, whereas the second by Fe^{+16}. A likely explanation is that the first event was caused by sheath southward IMFs (shocked, slow solar wind plasma and fields) and the second was from the remnants of the ICME itself (magnetic cloud). The peak *Dst* for the first event was -100 nT and -300 nT for the second event. We note however that these values were not pressure-corrected. The field at the storm initial phase was +60 nT indicating that the correction will be substantial.
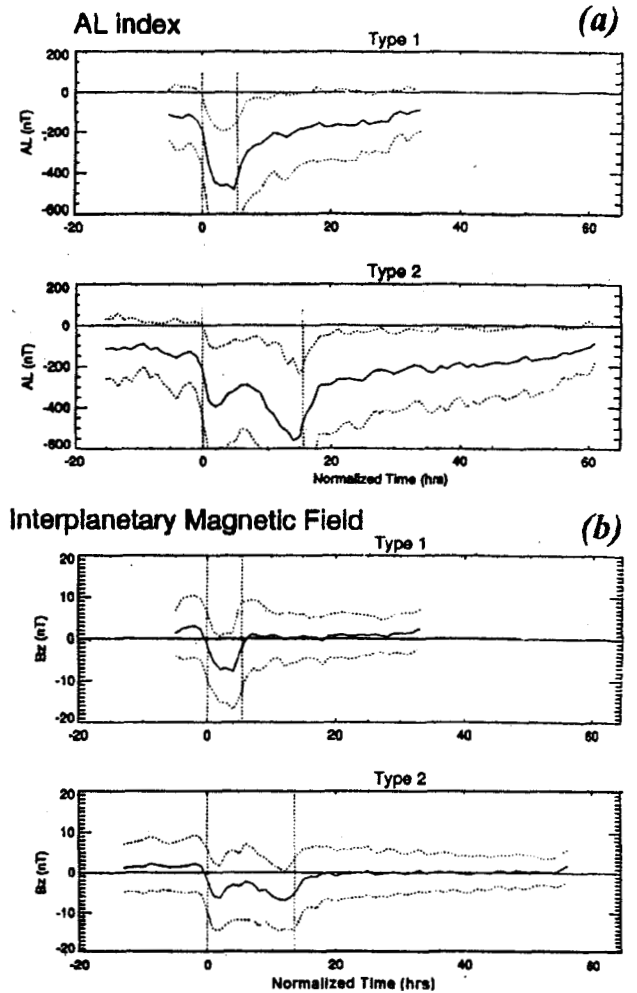
We reexamine the interplanetary causes of great

Figure 5. Normalized time series of (a) the AL index showing the development of single (top panel) and double (second panel) geomagnetic storms, and (b) the corresponding IMF B_z components showing the southward turning of the field which induces the response in the AL index shown in (a), as reported by Kamide et al. [1998].

magnetic storms ($Dst < -250$ nT) which have corresponding interplanetary data [reported in *Tsurutani et al.*, 1992]. The Dst profiles are shown in Figure 6. Three of the four largest events have complex main phases. The April 12-13, 1981 and the July 13-14, 1982 events are double main phase storms. The September 4-6, 1982, and the February 7-9, 1986 storms had a main phase that took days to develop, and can be viewed perhaps as triple-step storms. The latter could be due to a complex ICME/sheath region and to a precursor B_s field ahead of the shock.
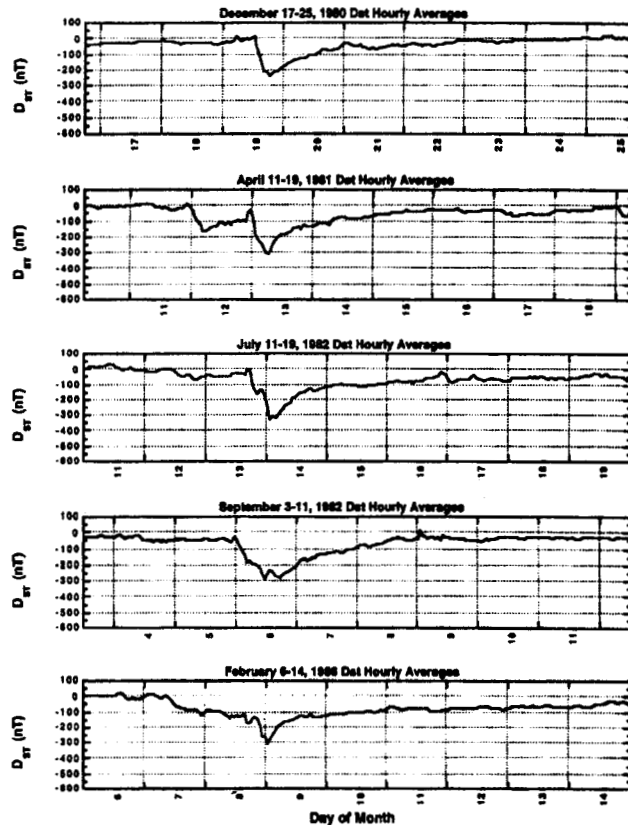

Figure 6. The five largest magnetic storms during the period from 1980 through 1986.

5. Superintense Magnetic Storms

Some of the largest magnetic storms registered since the Dst index became available (1957) occurred in the 1957-1959 era. These events occurred prior to the advent of in situ space plasma measurements. However, with our recent knowledge of the interplanetary causes of magnetic storms, we can make an educated guess as to their interplanetary causes. Figure 7 shows the profile of the three storms that had (uncorrected) peak Dst values < -400 nT. There is one event for each of the years 1957 through 1959. The main phases of each

of the three storms are relatively short, all less than 12 hours. The July 15, 1959 event was clearly a double storm event, whereas the September 13, 1957 event appears as a triple storm event.
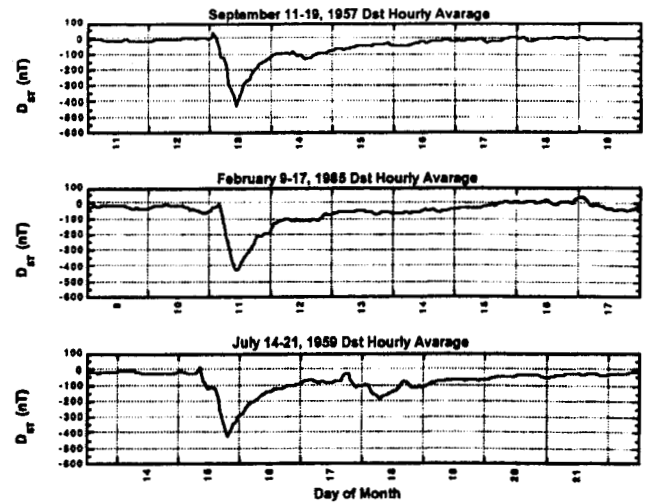

Figure 7. The three largest magnetic storms during the period from 1957 through 1959.

We also display the March 13-14, 1989 event, the largest recorded during recent times ($Dst = -600$ nT, uncorrected for pressure). This is shown in Figure 8. There is a slowly developing main phase prior to a sharp Dst decrease at $\sim$20 UT day 13. This profile is similar to the February 7-9, 1986 event discussed previously. The whole main phase takes over 24 hours. This most certainly indicates the presence of a complex sheath region existing ahead of a magnetic cloud. The storm profile indicates that this may be viewed as a triple storm event.
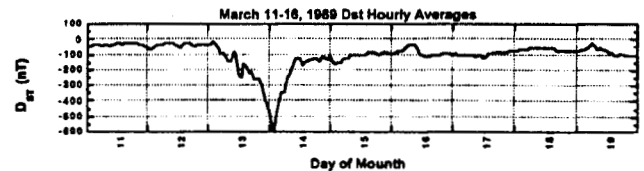

Figure 8. The largest geomagnetic storms appearing in the Dst record.

6. Discussion

Since for magnetic clouds the total field typically has a substantial southward component [*Gonzalez et al.*, 1994], the results shown on Figure 2 imply that

the interplanetary dawn-dusk electric field, given by $V_{sw} \times Bs$ is enhanced by *both* factors. Therefore, the consequent magnetospheric energization (that is governed by this electric field) becomes more efficient for the occurrence of magnetic storms, which at extreme conditions can drive very intense storms.

Although the 1957-1996 interval did not have sufficient interplanetary data available to examine the causes of all of the very intense storms, use of existing Dst profiles can allow one to make reasonable hypotheses of the interplanetary causes of such events. It is found that double and triple storms caused by two and three IMF B_s events may contribute significantly to the occurrence of very intense storms. We found no evidence of double shock events causing $Dst < -400$ nT magnetic storms. However, it should be noted that the storm sample used was quite limited.

We have only discussed obvious cases where double main phase storms have led to very intense storm events. Clearly, if a southward oriented sheath field region is followed by a magnetic cloud with a south-north orientation, the two main phases of the storm might be hard to identify using only the Dst data.

For the triple-step storms, in addition to the sheath and magnetic cloud fields, there is a need of an additional B_s structure. This would show up as a second stage sheath field (for example, due to a second shock) or to a substantial B_s field already existing ahead of the shock. Another possibility could be if the ICME/sheath system is closely followed by another interplanetary structure with a substantial B_s field, such as another stream or a kinky heliospheric current sheath [*Tsurutani et al.*, 1984].

What can be the magnetospheric causes of such double and triple storm effects? One speculation is that stochastic electric fields drive plasmasheet old ring current particles deep into the magnetosphere where the second and third storm fields do not sweep them out. Thus there would be residual ring current particles left over and the new ring current is simply added, giving a much larger Dst. Another possibility is that the first storm may have "primed" the plasma sheet for the second and the third event. *Borovsky et al.* [1997] have shown that the plasmasheet can be "superdense" at times and *Kozyra et al.* [1998] have shown that this can lead to a larger ring current. *Tsurutani et al.* [1998] have discussed one mechanism to provide an energetic oxygen enriched population to the plasmasheet. The above ideas are interesting but clearly more work is needed to determine the exact mechanism(s).

References

Borovsky, et al., *J. Geophys. Res.*, **102**, 22089, 1997.

Burlaga, L. F.., in *Interplanetary Magnetohydrodynamics* Oxford University Press, N. Y., 1995.

Burlaga, L. F.., et al., *J. Geophys. Res.*, **86**, 6673, 1981.

Daglis, I. A. in *Magnetic Storms, edited by B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo,* AGU Monograph, Washington, D.C. American Geophysical Union, Ser., 98, 107, 1997.

Dungey, J. W., *Phys. Rev. Lett.*, **6**, 47, 1961.

Gonzalez, W. D., and B. T. Tsurutani, *Planet. Space Sci.*, **35**, 1101, 1987.

Gonzalez, W. D., et al., *J. Geophys. Res.*, **99**, 5771, 1994.

Gonzalez, W. D., et al., *Geophys. Res. Lett.*, **25**, 963, 1998.

Grande, M., et al., *J. Geophys. Res.*, **101**, 24707, 1996.

Kamide, Y., et al.,*J. Geophys. Res.*, **103**, 6917, 1998.

Kennel, C. F. et al., in *Collisionless Shocks in the Heliosphere, edited by R. G. Stone and B. T. Tsurutani,* AGU Monograph, Washington, D.C. American Geophyseical Union, Ser., 34, 1, 1985.

Kozyra, J. U. et al., in *Proc. 4th Intern. Conf. on Substorms,* edited by Y. Kamide, Tokyo. Terra Scientific Publishing Company, Abstract 5-02, 80, 1998.

Smith, E. J. and C. P. Sonett, *Space Sci. Rev.*, **19**, 661, 1976.

Tsurutani, B. T., et al., *Geophys. Res. Lett.*, **11**, 339, 1984.

Tsurutani, B. T., et al., *Geophys. Res. Lett.*, **19**, 73, 1992.

Tsurutani, B. T., et al., *J. Geophys. Res.*, **100**, 21717, 1995.

Tsurutani, B. T. and W. D. Gonzalez, in *Magnetic Storms, edited by B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo,* AGU Monograph, Washington, D.C. American Geophysical Union, Ser., 98, 77, 1997.

Tsurutani, B. T., et al., *J. Geophys. Res.*, **103**, in press, 1998.